Replika Mirrors - Nearly Loss-Free Guides For Ultracold Neutrons

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Abstract

The reflectivity of ultracold neutron (UCN) guides produced with a dedicated technique called Replika has been studied. The guides are made of nickel, where the surface quality was copied from a glass layer. This results in a surface roughness smaller than 10 Å. The reflectivity was measured to be 99.9 % or higher. Those guides can be used at present or future UCN sources to transport UCN over long distances to the respective experiments without significant losses.

Key words: Ultracold neutrons, Replika, Neutron guides, Reflectivity
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1. Introduction

Ultracold neutrons (UCN) have velocities below 10 m/s and wavelengths around 1000 Å. They are totally reflected under each angle of incidence from certain materials and hence storable for hundreds of seconds in volumina made of those materials. This remarkable feature has put UCN in a favorite role to investigate fundamental properties of the neutron like its lifetime [1,2], its electric dipole moment [3,4], or its quantum states in the Earth's gravitational field [5].
UCN are guided in reflective tubes from the source to the experiment. The roughness of the guide surface is crucial for its transport properties. On rough surfaces, neutrons are non-specular reflected, resulting in a diffusive transport. Therefore the number of reflections for a neutron to travel a given distance decreases compared to a smooth surface with specular reflection and the transmission of the guide will be reduced significantly. To overcome this loss, essential R&D work on UCN guide properties is carried out at many laboratories [6,7,8,9,10,11,12].
The UCN guides we report on are made of a metallic surface with a high Fermi potential - natural nickel - whose high neutron-optical quality is achieved in a replication process first used for UCN application some 20 years ago [13]. The technique has been revisited by the Sputter-Dünnschicht company in Heidelberg (S–DH).

2. Interaction of UCN with material surfaces – UCN transport

The coherent interaction of neutrons with a surface is described by the Fermi-Potential $V_f = V + iW$, where V and W depend on the nuclear properties of the surface atoms seen by the neutrons [14]. The real part of the potential V sets a critical velocity $v_c = \sqrt{2V/m}$, with the neutron mass m. Neutrons with a normal velocity component $v_\perp < v_c$ are totally reflected from the surface with a probability given by the reflectivity coefficient $R = 1 - 2\,\frac{W}{V}\left(\frac{v_\perp^2}{2\,V/m - v_\perp^2}\right)^{1/2}$.
The dimensionless ratio $\eta = W/V$ is called the energy-independent wall-loss probability per bounce. It describes the UCN losses on the surface material due to absorption and inelastic scattering.
Nickel is commonly used as guide material due to its high Fermi-Potential of V=252 neV, which corresponds to a critical velocity $v_\mathrm{c} = 7$ m/s. For UCN with velocities close to the critical velocity v_c, the reflectivity decreases rapidly. However, sufficiently below v_c the reflectivity remains higher than 99.9 %.
Such a high reflectivity would allow nearly loss-free UCN transportation if only some hundreds of reflections over typical distances of meters to the experiment are needed as it is the case for specular transport. This is no longer true, however, if non-specular reflections come into play. In

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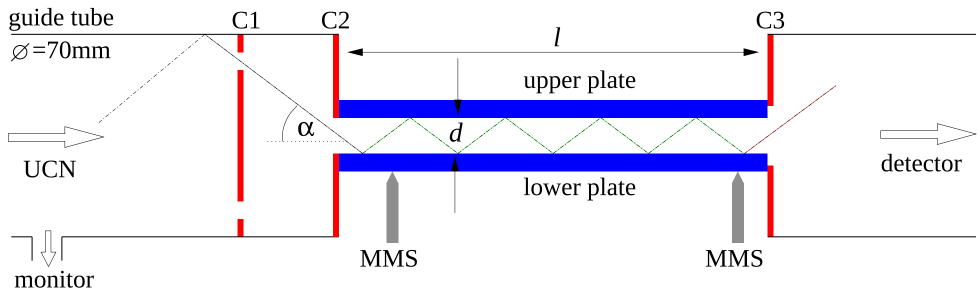

Fig. 1. Experimental set-up (not to scale). UCN from the Steyerl turbine at ILL pass the collimation C1 (two symmetrical openings up and down) and the transport channel between two parallel plates and leave towards the detector. The adjusted distance as shown in the draft would correspond to $d = 2$ mm. For larger distances, the UCN see the same opening angle into the channel and do not collide with the lower plate. The whole set-up was placed in vacuum at a pressure below 5×10^{-4}mbar.

first order, the probability for diffusive reflection of a wave on a rough surface is given by $(\Delta d/\lambda)^2$, where Δd is the average surface roughness and λ the normal wavelength component. Therefore, for low loss transportation of UCN, the surface roughness has to be smaller than 50 Å to avoid diffusive loss rates exceeding those from absorption and inelastic scattering.

3. Replika guides

At the UCN facility PF2 [13] of the Institut Laue Langevin (ILL), very cold neutrons ($v < 100$ m/s) are extracted vertically from the liquid D_2 source of the high-flux reactor towards the so-called Steyerl-turbine, where they are Doppler-shifted to the UCN regime. The cryogenic vertical guide, the curved feeding guide, the turbine blades and the following exit guides are made of nickel on an all-metal basis. A detailed description is given in [13]. The main idea of this so-called Replika technique is to copy the surface quality of a glass substrate to the guide surface. These metal guides offer high mechanical flexibility and stability and withstand the high radiation level close to the reactor core. The revisited Replika plates were manufactured at S–DH in the following way: 2000 Å nickel was sputtered onto Borofloat glass, gently solved, and then glued up-side-down onto an Aluminum plate as mechanical support. The dimensions of the plates are $500 \times 70 \times 8$ mm^3. The roughness was measured using x-rays to be less than 10 Å over the whole surface.

4. Measurement of the reflectivity

To measure the neutron reflectivity of such Replika plates, two of them are installed as a neutron guide of length $l = 500$ mm with open sides, as shown in fig. 1. Two collimators C1 and C2, made of cadmium, define a mean angle $\alpha = (40 \pm 6)^\circ$, under which UCN can enter the guide. The upper plate is fixed, while the lower one is vertically movable. The distance d between the plates is adjustable by means of micrometer-screws (MMS) with a reproducibility $\delta d < 0.05$mm. UCN have to undergo many specular reflections before being counted in the detector. Those UCN, which leave the horizontal parallel plate system to its open sides, are immediately absorbed to avoid reentering. A monitor in front of the guide monitors the flux of the incoming UCN. Gaseous detectors with low ^{3}He admixtures are used. Count rates were around 0.3 cps and 1 cps for the detector and the monitor, respectively.

The average UCN velocity at the TES position of the PF2 facility is ~ 8 m/s.

The background of the detector was measured by a) putting an UCN absorber between the plates and by b) closing the diaphragm C3 towards the detector completely. Both measurements yield a similar background rate around 8×10^{-3} cps. This implies that the background mainly arises from thermal reactor neutrons which can penetrate the detector shielding. The background rate of the monitor was found to be negligible.

5. Analysis

Fig. 2 shows the counts T of the detector after background correction and normalization to the monitor data. T decreases with smaller distances between the plates as expected: For smaller distances the number of specular reflections increases, according to $n(\alpha) = l/d \tan\alpha$, while the

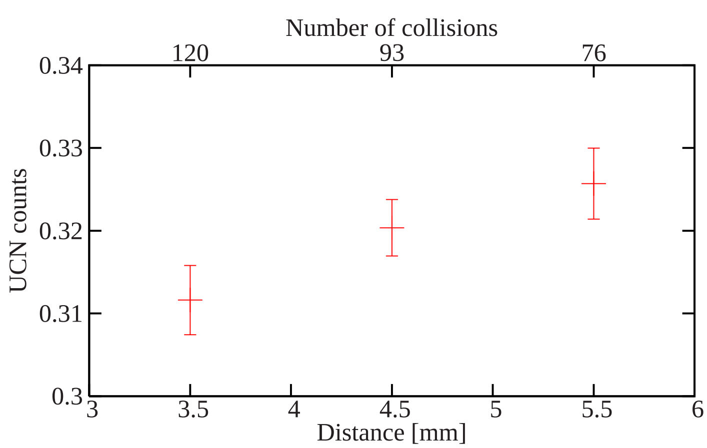

Fig. 2. Normalized counts T as a function of the distance between the plates. The indicated number of collisions are calculated for the mean angle of incidence $\alpha = 40^\circ$.

detection probability decreases with $T \propto R^n$.
The ratio of two measured T values at different distances d can be expressed by:

$$\frac{T_1}{T_2} = \frac{\langle R^{n_1(\alpha)} \rangle_\alpha}{\langle R^{n_2(\alpha)} \rangle_\alpha} = \frac{\langle R^{l/d_1 \tan\alpha} \rangle_\alpha}{\langle R^{l/d_2 \tan\alpha} \rangle_\alpha}. \tag{1}$$

The term on the right hand side is calculated numerically as a function of the reflectivity R and is compared to the measured count ratios. An isotropic UCN distribution between $\alpha_{\min}$ and $\alpha_{\max}$ is assumed. It was shown, that the results do not depend strongly on the form of the input distribution as only the difference in the number of reflections enters.
By evaluating the different combinations of the measured distances d we obtain a reflectivity of at least 99.9(1) %. The loss probability per bounce therefore is smaller than 10^{-3}.

6. Conclusion

All-metal guides produced by a replication process have shown their potential during more than 20 years of use at the UCN/VCN facility PF2 of the ILL. They offer high optical performance for both VCN and UCN, are resistant against high radiation and due to their thinness they are of high mechanical flexibility.
The revisited Replika technique yields guides with a surface roughness < 10 Å. Their reflectivity for UCN under realistic experimental conditions was measured to be at least 99.9(1) % per bounce, close to the theoretical expectations. With this technique, UCN guides of several meters length for new UCN sources, but also upgrades of existing guide systems, can be produced.

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